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Deficiency of large equivalent width Lyα emission in luminous Lyman break galaxies at $z \sim 5-6$?[1]

Masataka Ando[2], Kouji Ohta[2], Ikuru Iwata,[3]

Masayuki Akiyama[4], Kentaro Aoki[4], and Naoyuki Tamura,[4,5]

ABSTRACT

We report a deficiency of luminous Lyman break galaxies (LBGs) with a large rest-frame equivalent width ($\mathrm{EW_{rest}}$) of Lyα emission at $z \sim 5-6$. Combining our spectroscopic sample of LBGs at $z \sim 5$ and those from the literature, we found that luminous LBGs at $z \sim 5-6$ generally show weak Lyα emissions, while faint LBGs show a wide range of Lyα $\mathrm{EW_{rest}}$ and tend to have strong ($\mathrm{EW_{rest}} \gtrsim 20$Å) Ly$\alpha$ emissions; i.e., there is a deficiency of strong Lyα emission in luminous LBGs. There seems to be a threshold UV luminosity for the deficiency; it is $M_{1400} = -21.5 \sim -21.0$ mag, which is close to or somewhat brighter than the M_* of the UV luminosity function at $z \sim 5$ and 6. Since the large $\mathrm{EW_{rest}}$ of Lyα emission can be seen among the faint LBGs, the fraction of Lyα emitters in LBGs may change rather abruptly with the UV luminosity. If the weakness of Lyα emission is due to dust absorption, the deficiency suggests that luminous LBGs at $z = 5-6$ tend to be in dusty and more chemically evolved environments and that they start star formation earlier than faint LBGs, though other causes cannot be ruled out.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: high-redshift

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[1]Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

[2]Department of Astronomy, Kyoto University, Kyoto 606-8502, Japan.; andoh@kusastro.kyoto-u.ac.jp, ohta@kusastro.kyoto-u.ac.jp

[3]Okayama Astrophysical Observatory, National Astronomical Observatory, Kamogata, Okayama 719-0232, Japan.; iwata@oao.nao.ac.jp

[4]Subaru Telescope, National Astronomical Observatory of Japan, 650 North A'ohoku Place, Hilo, HI 96720.; akiyama@subaru.naoj.org, kaoki@subaru.naoj.org, naoyuki@subaru.naoj.org

[5]Department of Physics, University of Durham, Durham DH1 3LE, UK.

1. Introduction

Recently, a number of Lyman break galaxies (LBGs) at $z \sim 5-6$ have been found, and their photometric properties and spatial distribution have been studied extensively. Studies have been made on a UV luminosity function (UVLF) as well as a star formation rate (SFR) density at the epoch (e.g., Iwata et al. 2003; Bunker et al. 2004; Yan & Windhorst 2004; Dickinson et al. 2004; Ouchi et al. 2004a; Shimasaku et al. 2005; Bouwens et al. 2006) and on a two-point correlation function which constrains the mass of the dark halo where a LBG (or LBGs) resides (e.g., Ouchi et al. 2004b; Kashikawa et al. 2006). Furthermore, analysis of spectral energy distributions (SEDs) has constrained their stellar masses, ages, degree of extinction, and so on for the $z \gtrsim 5$ LBGs (e.g., Eyles et al 2005; Yan et al. 2005; Chary, Stern & Eisenhardt 2005; Schaerer & Pello 2005).

However, the spectroscopic properties of LBGs at $z \gtrsim 5$ are still unknown. Only about a dozen spectra have been published so far (Spinrad et al. 1998; Dey et al. 1998; Weymann et al. 1998; Dawson et al. 2002; Lehnert & Bremer 2003; Stanway et al. 2003, 2004; Nagao et al. 2004; Dow-Hygelund et al. 2005; Nagao et al. 2005), and extensive follow-up spectroscopies have been currently made. Among these, most of the spectra show only Lyα emission, and virtually no information can be drawn from their continuum spectrum. Frye et al. (2002) successfully detected the continuum and line features of gravitationally lensed galaxies at $z = 4 \sim 5$ and have found the presence of interstellar absorption lines. More recently, Dow-Hygelund et al. (2005) detected the continuum and interstellar absorption lines of an gravitationally lensed LBG at $z = 5.5$ with a good signal-to-noise (S/N) ratio with an extremely long (22.3 hours) exposure time.

We are also conducting a spectroscopic study of LBGs at $z \sim 5$ found by Iwata et al. (2003) and Iwata et al. (in preparation), and Ando et al. (2004) present the first results. The obtained spectra show no or weak Lyα emission in contrast to LBGs at $z \sim 3$ (e.g., Shapley et al. 2003; Iwata, Inoue & Burgarella 2005a), and rather strong low-ionization interstellar (LIS) absorption lines of which equivalent widths (EWs) are comparable to those seen in LBGs at $z \sim 3$ (Shapley et al. 2003). We also found the Lyα emissions are redshifted by about $500-700$ km s^{-1} relative to the interstellar absorption lines in a part of them, which suggests the presence of an outflow in the LBGs at $z \sim 5$.

In this letter, we report a possible UV luminosity dependence of Lyα emission of LBGs at $z \sim 5-6$ using our previous and new spectroscopic sample together with those from the literature, and we discuss some possible causes. Throughout this paper, we adopt flat Λ cosmology, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1}Mpc^{-1}. The magnitude system is based on AB magnitude (Oke & Gunn 1983).

2. Spectroscopic Samples of LBGs at $z \sim 5$ and $z \sim 6$

The spectroscopic sample of LBGs at $z \sim 5$ is taken mainly from Ando et al. (2004) and our recent results taken with FOCAS (Kashikawa et al. 2002) attached to the Subaru telescope (Iye et al. 2004). The former sample is obtained around the GOODS-N field and the latter one is obtained around the J0053+1234 field (see Ando et al. 2005). The LBG selection of our sample is based on $V - I_C$ and $I_C - z'$ colors, and details are described in Iwata et al. (2003, 2005b) and Iwata et al. (in preparation). Magnitudes of the spectroscopic sample in the I_C band are $24.0 - 25.3$, and the redshift coverage is $z = 4.3 - 5.2$. The spectroscopic observations and data reductions are achieved by almost the same way for both samples as described in Ando et al. (2004). For the sample in the GOODS-N field, resulting spectra of 7 bright ($I_C \leq 25.0$) LBGs are shown in Figure 1 of Ando et al. (2004). They show the continuum depression shortward of redshifted Lyα and some LIS metal absorption lines, indicating secure identifications of the redshifts. For the sample in the J0053+1234 field, 2 bright ($I_C \leq 25.0$) LBGs were confirmed with the similar features to the GOODS-N sample, and 2 faint ones were identified with a strong ($\mathrm{EW_{rest}} \sim 40 - 80$Å) Ly$\alpha$ emission line. The average Lyα $\mathrm{EW_{rest}}$ of our 9 bright spectroscopic LBGs is $\sim 6 \pm 7$Å, and that of 2 faint ones is $\sim 60 \pm 20$Å. In addition to our sample, we take the spectral data of similar redshifts from the literature (Spinrad et al. 1998; Dey et al. 1998; Dawson et al. 2002; Lehnert & Bremer 2003). The number in the sample is 6, and the redshift coverage is $z = 4.8 - 5.3$. Since the sample of Frye et al. (2002) is gravitationally lensed and their magnitude correction contains a relatively large uncertainty (maximally 1.5 mag), it is excluded in the following discussion.

We also compiled spectroscopic results of LBGs at $z \sim 6$ (Weymann et al. 1998; Lehnert & Bremer 2003; Stanway et al. 2003, 2004; Nagao et al. 2004; Dow-Hygelund et al. 2005; Nagao et al. 2005). The number of galaxies in the sample is 9, and the redshift coverage is $z = 5.5 - 6.3$. The object by Dow-Hygelund et al. (2005) is a gravitationally lensed galaxy. But its amplification effect (~ 0.3 mag at most) is small, and thus we include it. Note that the objects by Nagao et al. (2004, 2005) are the i'-dropout objects with narrow band (NB921) depression; a strong Lyα emission largely contributes to the z'-band light.

3. Result and Discussion

3.1. Deficiency of UV luminous LBGs with a large Lyα equivalent width

With the samples described in section 2, we adopted EWs of Lyα emission appeared in each paper. For the objects of our spectroscopic sample of LBGs at $z \sim 5$ in the J0053+1234 field, we measured EWs by the same way used in Ando et al. (2004). The uncertainties of

the EWs are estimated to the 30-50%. For the sample of Lehnert & Bremer (2003), we measured the EWs from their Figure 4 because the EWs of individual objects were not presented. The uncertainties of EWs are roughly 50%. For all these values of EWs, the absorption for the emission line by intergalactic matter (IGM) was not corrected, and the absorption component of Lyα was not included. Figure 1 shows rest EWs of Lyα emissions plotted against the rest-frame UV absolute magnitudes. Filled circles show our spectroscopic results, and filled squares refer to the results from the literature. Open squares represent those of LBGs at $z \sim 6$. We converted the observed broad band magnitude to the rest-frame 1400Å magnitude assuming a continuum slope β ($f_\lambda \propto \lambda^\beta$) of -1 which is a typical value for LBGs at $z \sim 3$ (Shapley et al. 2003). The effect of the uncertainty of the slope is small and estimated to be typically $0.1-0.2$ mag. For the objects whose adopted broad band contained the wavelength region shortward of Lyα, we corrected for the contributions by Lyα emission and IGM absorption (Madau 1995) to derive the UV absolute magnitudes. From the UV absolute magnitude using the relation by Madau, Pozzetti & Dickinson (1998), we also show the SFR estimated at the upper abscissa.

As seen in Figure 1, there are no UV luminous ($M_{1400} \lesssim -21.0$ mag) LBGs at $z \sim 5$ with strong (EW$_{\rm rest}$ $\gtrsim$20Å) Lyα emission, while UV faint ones show wide range of EW$_{\rm rest}$ and tend to have stronger Lyα emission than UV luminous LBGs on average. In addition, there seems to be a UV magnitude threshold for LBGs with strong Lyα emission around $M_{1400} \sim -21.0$ mag which is almost the same as the M_* magnitude of the UVLF of our $z \sim 5$ LBG sample (Iwata et al. 2003) and that of Ouchi et al. (2004a). This trend still holds if the data by Frye et al. (2002) are considered.

A similar deficiency of the luminous LBGs with strong Lyα emission seems to hold at $z \sim 6$, although the sample size is quite small especially for a luminous part ($M_{1400} \lesssim -21.5$ mag). There seems to be the threshold magnitude around $M_{1400} \sim -21.5$ mag which is close to the M_* of the UVLF at $z \sim 6$ of Bunker et al. (2004) and ~ 1.4 mag brighter than that of Bouwens et al. (2006). The threshold magnitude is ~ 0.5 mag brighter than that of LBGs at $z \sim 5$, which might suggest its evolution. But the current sample number is not large enough to be definitively to illustrate the evolution of the threshold magnitude.

We note that the deficiency of the luminous LBGs with strong Lyα emission is not due to observational bias at least for our spectroscopic sample. First, the minimum detectable EW$_{\rm rest}$ of the Lyα emission in our spectroscopic survey is $\sim$10Å for luminous (corresponding to $I_C \leq 25.0$) LBGs at $z \sim 5$, and $\sim$30Å for faint ones, respectively, in the wavelength regions where night sky emission lines are not strong. Therefore, we should detect large EW Lyα emission lines among luminous LBGs, if there are such objects. Second, the number of the *observed* luminous LBGs in our present spectroscopic sample (22 objects) is larger

than the number of the faint ones (12 objects). Thus, if the fraction of objects with strong Lyα emission is the same for UV luminous and faint LBGs, we should detect at least several luminous LBGs with strong Lyα emission, unless we happened to choose LBG candidates with a small $\mathrm{EW_{rest}}$ in luminous candidates selectively. The Kolmogorov-Smirnov test would not be useful because faint LBGs with a small $\mathrm{EW_{rest}}$ are expected to be missed in the present sample.

For the $i-z$ selected LBGs at $z \sim 6$, there may be a selection bias which leads to the apparent deficiency of LBGs with strong Lyα emission because the strong Lyα emission contributes largely to the i-band flux and reduce the value of the $i-z$ color. Expected $i-z$ colors of the LBGs with rest EW of 20(100)Å are ~ 0.2 mag (~ 0.7 mag) bluer than $i-z = 1.5$ mag, the color criterion to pick up i-dropout objects, in the redshift range between ~ 5.9 to ~ 6.0 (between ~ 5.9 to ~ 6.1) [1]. Among the samples we used here, Stanway et al. (2003) and Dow-Hygelund et al. (2005) utilized the $i-z$ selection method, and the samples may suffer from the selection bias. However, this bias should work independently of the UV luminosity, thus it may not seriously affect the deficiency of luminous LBGs with strong Lyα. Note that the sample of LBGs at $z \sim 5$ does not suffer from this selection bias.

Since the $\mathrm{EW_{rest}}$ increases with decreasing UV continuum luminosity for a constant Lyα luminosity, the deficiency may just reflect the distribution of a constant Lyα luminosity. In Figure 1, we show locations of constant Lyα luminosity corresponding to 5×10^{43}, 2×10^{43}, 10^{43}, 5×10^{42}, and 10^{42} erg s^{-1} with dotted lines from top-left to bottom-right. All the luminous LBGs with small EWs have Lyα luminosity smaller than or equal to 10^{43} erg s^{-1}, while about a half of the faint LBGs show Lyα luminosity larger than 10^{43} erg s^{-1}. Although the contrast is not so strong as compared with that seen in the EWs, again there are no UV luminous LBGs having a large Lyα luminosity. In any cases, the present sample is a combination of our spectroscopic data and those from the literature, and the sample size is small. A more homogeneous and larger spectroscopic sample is needed to examine whether this trend is definitive or not, although such data sets are hard to obtain even with currently available 8-10m telescopes.

3.2. Lyman α emitters at $z \sim 6$

Since Lyα emitters (LAEs) are expected to have large rest EWs due to their selection method, LAEs may be located in the upper left part of the Figure 1. We plot LAEs at

[1]The expected color and affected redshift range depend somewhat on the adopted spectral templates of star-forming galaxies.

$z \sim 5.7$ and $z \sim 6.6$ detected from narrow-band imaging data in Figure 1; crosses and pluses represent LAEs at $z \sim 5.7$ (Ajiki et al. 2003) and LAEs at $z \sim 6.6$ (Taniguchi et al. 2005), respectively. We adopted values of EWs from spectroscopic results for a part of LAEs at $z \sim 6.6$ (triangles: Taniguchi et al. 2005). The values of Lyα rest EWs are not corrected for IGM absorption for the emission. Most of the LAEs are UV faint objects and the rest EWs distribution is similar to that of faint LBGs. For the UV luminous LAEs, Lyα rest EWs are relatively smaller than those of faint LAEs and faint LBGs, and again we can see the deficiency of the strong Lyα emission in UV luminous LAEs. A recent survey of LAEs at $z = 5.7$ in the Subaru Deep Field (Shimasaku et al. 2006) also shows the same tendency (see their Figure 16).

These results imply that a fraction of LAEs in LBGs changes with the UV luminosity at $z \sim 5 - 6$; among UV luminous LBGs, there are only a few LAEs, while among faint LBGs there are many LAEs with large EW of Lyα emission. This fits the trend that the ratio of LAEs to LBGs at $z \sim 5$ decreases with increasing UV luminosity (Ouchi et al. 2003), although our results show a rather abrupt decrease of LAEs among luminous LBGs. Thus, the LAEs are presumably a subset of faint LBGs, and are not the luminous LBGs at the redshift.

3.3. Possible origins of the deficiency

Although we need further studies to confirm this deficiency of the luminous LBGs with a large Lyα $\mathrm{EW}_{\mathrm{rest}}$, we try to find possible causes for the trend and its implications. One possible cause is the systematic difference of the dust extinction between luminous and faint LBGs. Since there are significant correlations between gas metallicity, dust extinction, and strength of LIS absorption lines in local star-forming galaxies (e.g., Heckman et al. 1998), the presence of strong LIS absorption lines in the luminous LBGs of our spectroscopic sample support this possibility. If we assume the local relation between the EW of LIS absorptions and metallicity by Heckman et al. (1998), an estimated gas metallicity for our spectroscopic sample of luminous LBGs at $z \sim 5$ is 12+log(O/H)~ 8.0 ($\sim$1/5 solar: using the solar value from Allende Prieto, Lambert & Asplund 2001). At this gas metallicity, the Lyα/Hβ ratio is reduced by a factor of about 30 from the Case B assumption for local star-forming galaxies (Hartmann et al. 1988). If the luminous LBGs at $z \sim 5$ are more chemically evolved than the faint LBGs, it is suggested that the luminous LBGs at $z \sim 5$ started star formation relatively earlier than faint ones. The clustering analysis of LBGs at $z \sim 5$ shows that luminous LBGs have a larger correlation length than faint ones, suggesting luminous LBGs reside in a more massive dark halo (e.g., Ouchi et al. (2004b); Iwata et al. in preparation). The suggestions

seem to fit the biased star formation scenario in the early universe; UV luminous LBGs at $z \sim 5$ are in a more massive dark halo and have experienced star formation earlier than faint ones residing in a less massive dark halo. We do not find the significant relation between the $I_C - z'$ color and the $\mathrm{EW_{rest}}$ of Lyα emission for our spectroscopic sample. However, this is probably because the baseline separation between I_C and z' is too small to derive reliable $E(B-V)$ values under the current photometric uncertainty. In addition, the S/Ns of our spectra are too low and the wavelength coverage is too small to reliably estimate the $E(B-V)$ values from their continuum.

The amount of HI gas in and surrounding the galaxy can affect the Lyα EWs. If luminous LBGs have much more HI gas than faint ones, it is possible that Lyα emission is selectively extinguished in luminous LBGs, resulting in small EWs. The presence of a large amount of HI gas in luminous LBGs seems to fit the biased galaxy formation scenario described above; luminous LBGs reside in a more massive dark halo are expected to have more HI gas than faint ones in a less massive dark halo.

The age of a galaxy can also affect the EW of Lyα. A large Lyα $\mathrm{EW_{rest}}$ (100-200Å) is expected for very young ($< 10 - 100$Myr) galaxies (e.g., Charlot & Fall 1993). Thus the luminous LBGs may be rather older than faint ones. However, it is hard to claim so, if the dust exists in a galaxy. In fact, using the results of SED fitting of LBGs at $z \sim 3$, Shapley et al. (2001) found that the composite spectrum of young (age $\leq$ 10Myr) LBGs shows a small Lyα EW, while that of old (age $\geq$ 1Gyr) LBGs shows a large one.

Another possibility is velocity structure of the HI gas in/around the galaxy. From Lyα imaging and spectroscopy of nearby star-forming galaxies, EWs of Lyα do not necessarily depend on the gas metallicity. For example, Kunth et al. (1998, 2003) claims that the kinematical property of the gas is a dominant regulator of the Lyα escape probability; galaxies with outflowing neutral gas tend to have large Lyα EWs, while galaxies with static neutral gas tend to have small Lyα EWs. Shapley et al. (2003) also pointed out the importance of the kinematical feature for the LBGs at $z \sim 3$, but their sense of effect on Lyα EW is opposite to that of Kunth et al. (1998). They found that LBGs with smaller Lyα EWs tend to have stronger LIS absorptions and large velocity offsets of Lyα emission relative to LIS absorption lines. These facts can be explained if the LBGs with smaller EWs have outflowing neutral gas with a larger velocity dispersion, because the gas causes a broader Lyα absorption for Lyα emission that results in a smaller EW of Lyα, a more redshifted (asymmetric) Lyα peak that is seen as the larger velocity offset between Lyα and LIS absorption, and stronger LIS absorption lines (Shapley et al. 2003). We found the asymmetry of the Lyα emission line and the velocity offset of Lyα emission relative to LIS absorption lines in a part of our luminous spectroscopic sample, which implies the presence of the large-scale motion of the

neutral gas of LBGs at $z \sim 5$ as well as at $z \sim 3$. Thus there is a possibility that the gas kinematics affects the EW and the shape of profile of Lyα emission.

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REFERENCES

Allende Prieto, C., Lambert, D. L., & Asplund, M. 2001, ApJ, 556, L63

Ajiki, M., et al. 2003, AJ, 126, 2091

Ando, M., Ohta, K., Iwata, I., Watanabe, C., Tamura, N., Akiyama, M., & Aoki, K. 2004, ApJ, 610, 635

Ando, M., Ohta, K., Iwata, I., Akiyama, M., Aoki, K., & Tamura, N. 2005, to appear in 'THE FABULOUS DESTINY OF GALAXIES : BRIDGING PAST AND PRESENT', astro-ph/0510830

Bouwens, R. J., Illingworth, G.D., Blakeslee, J. P., & Franx, M. 2006, ApJ, in press (astro-ph/0509641)

Bunker, A. J., Stanway, E. R., Ellis, R. S., & McMahon., R. G. 2004, MNRAS, 355, 384

Charlot, S. & Fall S. S. 1993, ApJ, 415, 580

Chary, R., Stern, D. & Eisenhardt, P., 2005, ApJ, 635, L5

Dawson, S., et al., 2002, ApJ, 570, 92

Dey, A., Spinrad, H., Stern, D., Graham, J. R., & Chaffee, F. H., 1998, ApJ, 498, L93

Dickinson, M., et al. 2004, ApJ, 600, L99

Dow-Hygelund C. C., et al. 2005, ApJ, 630, L137

Eyles, L., Bunker, A., Stanway, E., Lacy, M., Ellis, R., & Doherty, M. 2005, MNRAS, 364, 443

Frye, B., Broadhurst, T., & Benitez, N. 2002,ApJ, 568, 558

Hartmann, L. W., Huchra, J. P., Geller, M. J., O'Brien, P. & Wilson, R. 1988, ApJ, 326, 101

Heckman, T. M., Robert, C., Leitherer, C.,Garnett, D. R., & van der Rydt, F. 1998, ApJ, 503, 646

Iwata, I., Ohta, K., Tamura, N., Ando, M., Wada, S., Watanabe, C., Akiyama, M., & Aoki, K. 2003, PASJ, 55, 415

Iwata, I., Inoue, A. K., & Burgarella, D. 2005a, A&A, 440, 881

Iwata, I., Ohta, K., Ando, M., Tamura, N., Kiuchi, G., Akiyama, M., & Aoki, K. 2005b, to appear in 'THE FABULOUS DESTINY OF GALAXIES : BRIDGING PAST AND PRESENT', astro-ph/0510829

Iye, M., et al. 2004, PASJ, 56, 381

Kashikawa, N., et al. 2002, PASJ, 54, 819

Kashikawa, N., et al. 2006, ApJ, 637, 631

Kunth, D., Mas-Hesse, J. M., Terlevich, E., Terlevich, R., Lequeux, J., & Fall, S. M. 1998, A&A, 334, 11

Kunth, D., Leitherer, C., Mas-Hesse, J. M., Östlin, G., & Petrosian, A. 2003, ApJ, 597, 263

Lehnert, M. D., & Bremer, M. 2003, ApJ, 593, 630

Madau P. 1995, ApJ, 441, 18

Madau P., Pozzetti, L., & Dickinson, M. 1998, ApJ, 498, 106

Nagao, T., et al. 2004, ApJ, 613, L9

Nagao, T., et al. 2005, ApJ, 634, 142

Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713

Ouchi, M., et al. 2003, ApJ, 582, 600

Ouchi, M., et al. 2004a, ApJ, 611, 660

Ouchi, M., et al. 2004b, ApJ, 611, 685

Schaerer, D., & Pello, R. 2005, MNRAS, 362, 1054

Shapley, A. E., Steidel, C. C., Adelberger, K. L., Dickinson, M., Giavalisco, M., & Pettini, M. 2001, ApJ, 562, 95

Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, ApJ, 588, 65

Shimasaku, K., Ouchi, M., Furusawa, H., Yoshida, M., Kashikawa, N. & Okamura, S. 2005, PASJ, 57, 447

Shimasaku, K., et al. 2006, PASJ, in press (astro-ph/0602614)

Spinrad, H., et al. 1998, AJ, 116, 2617

Stanway, E. R., Bunker, A. J., & McMahon, R. G. 2003, MNRAS, 342, 439

Stanway E., Bunker A., McMahon R., Ellis R. S., Treu T., & McCarthy P. J. 2004, ApJ, 607, 704

Taniguchi, Y., et al. 2005, PASJ, 57, 165

Weymann, R. J., Stern, D., Bunker, A., Spinrad, H., Chaffee, F. H., Thompson, R. I., & Storrie-Lombardi, L. J. 1998, ApJ, 505, L95

Yan, H., & Windhorst, R. A. 2004, ApJ, 612, L93

Yan, H., et al. 2005, ApJ, 634, 109

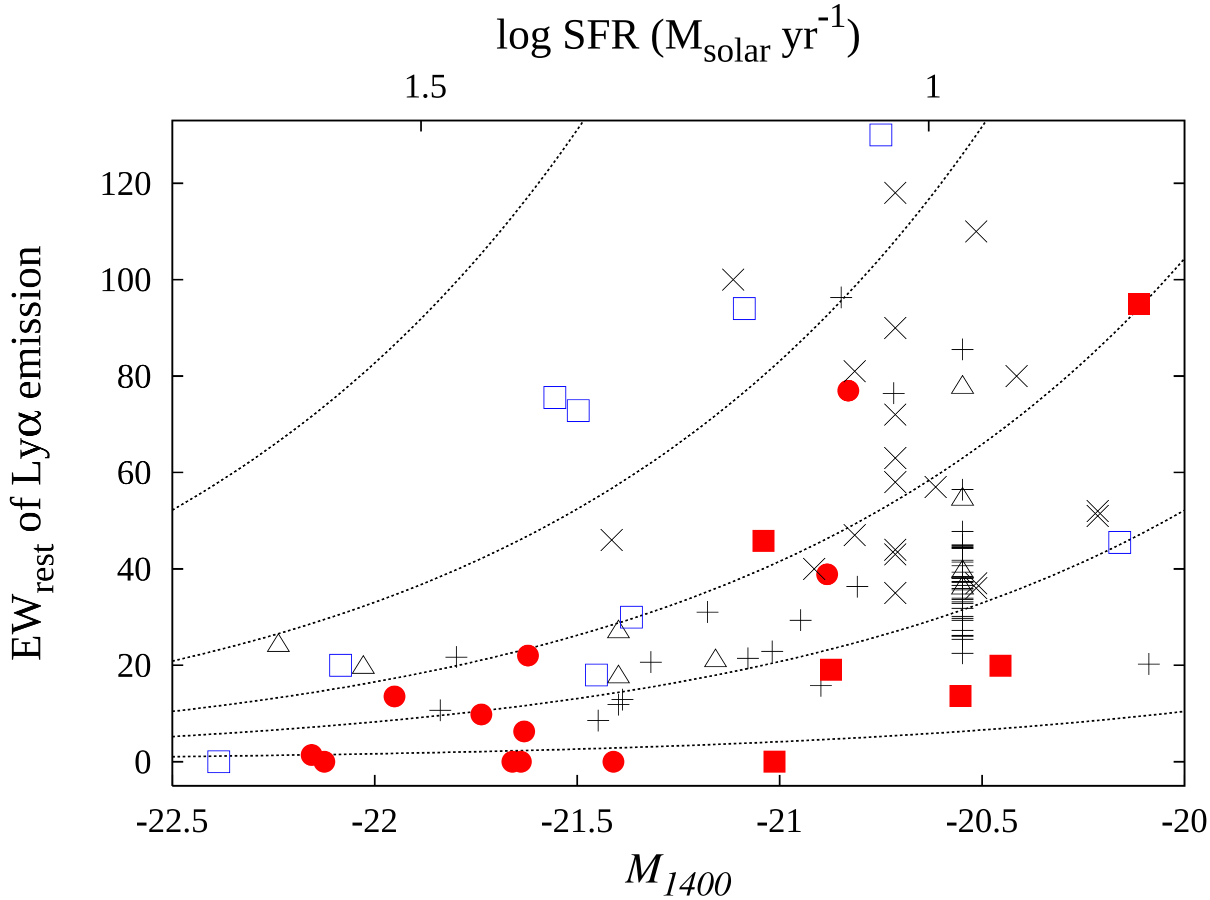

Fig. 1.— Rest-frame EWs of Lyα emission vs. absolute magnitude at rest-frame 1400Å for galaxies at $z \sim 5$. Filled circles show our previous (Ando et al. 2004) and newly added results. Filled squares show data taken from the literature (Lehnert & Bremer 2003; Spinrad et al. 1998; Dawson et al. 2002; Dey et al. 1998). Open squares show the data of galaxies at $z \sim 6$ taken from Weymann et al. (1998); Lehnert & Bremer (2003); Stanway et al. (2003, 2004); Nagao et al. (2004); Dow-Hygelund et al. (2005); Nagao et al. (2005). Crosses and pluses represent Lyα emitters at $z = 5.7$ and $z = 6.6$, respectively (Ajiki et al. 2003; Taniguchi et al. 2005), obtained from narrow-band imaging. A part of the sample of Taniguchi et al. (2005) have spectroscopic results of EW$_{\rm rest}$, and we plot them as triangles. Star formation rate (SFR) estimated from UV absolute magnitude (Madau, Pozzetti & Dickinson 1998) is also shown at the top. Dotted lines show Lyα EW$_{\rm rest}$ as a function of UV absolute magnitude for a constant Lyα luminosity of $5{\times}10^{43}$, $2{\times}10^{43}$, 10^{43}, $5{\times}10^{42}$, and 10^{42} erg s^{-1} from top-left to bottom-right.